Co-authorship proximity of A. M. Turing Award and John von Neumann Medal winners to the disciplinary boundaries of computer science

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Keywords: Biomedical sciences; Computer science; Cross-disciplinary brokers; Erdős numbers; Graph centrality; Interdisciplinarity

Abstract

It is shown that winners of the A. M. Turing Award or the John von Neumann Medal, both of which recognize achievement in computer science, are separated from some other A. M. Turing Award or John von Neumann Medal winner by at most 1.4 co-authorship steps on average, and from some cross-disciplinary broker, and hence from some discipline other than computer science, by at most 1.6 co-authorship steps on average. A. M. Turing Award and John von Neumann Medal recipients during this period are, therefore, on average closer in co-authorship terms to some other discipline that typical computer scientists are, on average, to each other.

Introduction

How are the most prominent and widely-recognized members of any scientific discipline distributed within the social network formed by that discipline? More specifically, how are the most prominent members of a discipline distributed within the co-authorship graph of that discipline? Studies of co-authorship paths traversing cross-disciplinary brokers (Fields, 2015) and of co-authorship connections of Nobel laureates in Physiology or Medicine (Fields, 2014; in press) suggest a surprising answer: prominent intellectual and, in many cases, political leaders of several disciplines appear to be located near the co-authorship boundaries of their disciplines, in close proximity to cross-disciplinary brokers. In some cases, such leading individuals are themselves cross-disciplinary brokers; Nobel laureates Donald Glaser (Physics, 1960), Francis Crick (Physiology or Medicine, 1962), Richard Feynman (Physics, 1965), Max Delbrück (Physiology or Medicine, 1969), Murray Gell-Mann (Physics, 1969) , Herbert Simon (Economics, 1978), Walter Gilbert (Chemistry, 1980), Tom Cech (Chemistry, 1989), Frederick Reines (Physics, 1995), Günter Blobel (Physiology or Medicine, 1999) and Peter Mansfield (Physiology or Medicine, 2003) are examples. This in turn suggests that the "centers" of disciplines, at least as defined informally by recognized scientific accomplishment, may be loci and possibly even the primary loci of inter- or transdisciplinary research activity. Were this to be demonstrated as a general phenomenon, the common idea that inter- or transdisciplinary activities, the scientists who engage in them and the organizational structures that support them are peripheral to mainstream disciplinary science and hence of relatively low academic value may require re-examination and possibly revision.

The present paper tests the suggestion that prominent disciplinary leaders may often be located near the co-authorship boundaries of their disciplines by examining co-authorship connections of the 61 recipients of the A. M. Turing Award, the closest equivalent to a Nobel Prize in computer science, from its inception in 1966 through 2013, the year of the most recent award. The A. M. Turing Award is presented by the Association for Computing Machinery (ACM), a professional society of computer scientists and others with an interest in computing. Nominations are solicited from "recognized member(s) of the community" whether or not they are ACM members.[1] Co-authorship connections of the 27 recipients of the comparable John von Neumann Medal, awarded to prominent computer scientists since 1992 by the Institute of Electrical and Electronics Engineers (IEEE), from its inception to 2015 are also examined. Nominations for the John von Neumann Medal are also open to all, regardless of membership in IEEE.[2] There is substantial overlap between these groups: 14/27 (52%) of John von Neumann Medal recipients are also A. M. Turing Award recipients. The 74 scientists who have won at least one of these two awards are, therefore, considered together as constituting the informal, accomplishment-based "center" of computer science for the purposes of this study.

Unlike physics or biomedicine, computer science is not a big science (De Solla Price, 1963) discipline in which many researchers have hundreds of collaborators and some papers have hundreds of co-authors. Newman (2001) reported an average of 3.6 collaborators per author among computer scientists during the period 1995 - 1999, compared to 18 for biomedical researchers and 9.7 for physicists. The mean distance between computer science researchers in the co-authorship graph during this period was 9.7, compared to 4.6 for biomedical researchers and 5.9 for physicists; the diameter (length of the longest minimal path) of the computer science co-authorship graph was 31, compared to 24 for the co-authorship graph of biomedicine and 20 for the co-authorship graph of physics (Newman, 2001). As a further comparison, Elmacioglu and Lee (2005) reported that the co-authorship diameter of just the database specialty of computer science was 20 in 2003 and the mean co-authorship distance of this specialty was 6 from 1990 to 2003, suggesting that the database specialty of computer science had roughly the co-authorship characteristics of the entire disciplines of physics or biomedicine during the same period. If the proximity of some prominent researchers in multiple disciplines to cross-disciplinary brokers reported in Fields (2015) is an artifact of initiating co-authorship searches at brokers (i.e. of ascertainment bias), and if the proximity of many recent Nobel laureates in Physiology or Medicine to the boundaries of their discipline (Fields, 2014; in press) is an artifact of the emergence of biomedical big science projects in the 1990s, one might expect these apparent patterns not to characterize computer science. One might, in particular, expect A. M. Turing award winners to be close to the center of computer science as measured by distance centrality, i.e. to be on the order of half the co-authorship graph diameter or roughly 10-15 co-authorship steps, on average, from the boundaries between computer science and other disciplines.

1 See http://amturing.acm.org/call_for_nominations.cfm; accessed Jan., 2015.
2 See http://www.ieee.org/about/awards/awards_guidelines.html; accessed Jan., 2015.

It is shown here that A. M. Turing Award and John von Neumann Medal winners from 1966 to 2015 are, on average, only 1.6 co-authorship steps away from at least one cross-disciplinary broker and hence at least one boundary between computer science and some other discipline. Like Nobel laureates in Physiology or Medicine, therefore, A. M. Turing Award and John von Neumann Medal winners are closer, on average, to other disciplines than typical members of their own discipline are, again on average, to each other. They are even closer, moreover, to their discipline's boundaries than are Nobel laureates in Physiology and Medicine between 1991 and 2010, for whom the average distance to some disciplinary boundary is 2.8 co-authorship steps (Fields, in press). This result shows that the proximity of prominent scientists to disciplinary boundaries observed previously cannot merely be an artifact either of the large collaborations and liberal co-authorship policies typical of big science projects or of initiating co-authorship searches from cross-disciplinary brokers. It is also shown here that the disciplines to which prominent computer scientists are closest have shifted significantly with time. A. M. Turing awardees during the first 10 years of the award (1966 – 1975) were closest to physics, with economics a close second, while Turing awardees during the last 10 years examined (2004 – 2013) were nearly all closest to the biomedical sciences, including neuroscience. The Erdős numbers – co-authorship distances to mathematician Paul Erdős – of A. M. Turing Award or John von Neumann Medal winners from 1966 to 2015 average 4.6, comparable to those of mathematicians (average 4.7; Grossman, 2005). This value is significantly less than that of the average Erdős number of Nobel laureates in Physiology or Medicine from 1991 to 2010 (5.5; Fields, in press) or the average Erdős number of the 13 Nobel laureates in Physics between 1991 and 2010 listed by the Erdős Number Project[3] (also 5.5), but is, interestingly, greater than the average Erdős number (3.2) of the Derek De Solla Price Memorial Medal awardees noted by Glänzel and Rousseau (2005).

Data and Methods

Names and research specialties of A. M. Turing Award and John von Neumann Medal winners were obtained from the ACM[4] and IEEE[5] respectively. Co-authorship data were obtained from Google Scholar™ as described (Fields, in press). Paths from awardees traversing other authors known to be near either other Turing or von Neumann awardees, cross-disciplinary brokers or Nobel laureates in some scientific discipline were followed preferentially. This is a tractable, greedy search procedure that produces upper limits on the minimal co-authorship path lengths from Turing or von Neumann awardees to other awardees, brokers, or Nobel laureates; more exhaustive, and in particular non-heuristic, search procedures may produce smaller path lengths in some cases. “Cross-disciplinary brokers” were defined as individuals who have published co-authored papers both in computer science and in at least one of the 15 other Klavans and Boyack (2009) consensus disciplines. Disciplinary assignments of papers were determined from the title, abstract and journal, proceedings or edited collection in which they were published, or if necessary, by reading the paper in its entirety. Only primary and secondary research papers, review articles, research-based science-policy papers and scholarly books were included in the co-authorship analysis; otherwise-unpublished technical reports, textbooks, joint editing of collections, and editorial or opinion pieces were not included. Papers meeting these content criteria that appeared in conference proceedings were included in the analysis, as

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3 http://www.oakland.edu/enp/erdpaths/; accessed Jan., 2015

4 http://amturing.acm.org/; accessed Nov. - Dec., 2014.

5 http://www.ieee.org/about/awards/medals/vonneumann.html; accessed Jan., 2015

conference proceedings are a recognized venue for refereed publications in computer science (Franceschet, 2010; Freyne, Coyle, Smyth and Cunningham, 2010). Where necessary, authors with similar names were disambiguated by tracing their histories of institutional appointments.

As a cross-check on the co-authorship results obtained from Google Scholar™ for computer scientists, their co-authorship connections were also examined using the DBLP Computer Science Bibliography of the Universität Trier,[6] imposing the same constraints for inclusion or exclusion of publications from the analysis as used earlier. The DBLP is primarily a computer-science resource, though it contains some papers from mathematics and formal logic journals. As a result, this second stage was only able to contribute some additional connections to mathematics to the cross-disciplinary co-authorship analysis. As some computer science papers found using Google Scholar™ were not found in DBLP and vice-versa, co-authorship distances greater than one must still be regarded as upper limits. A tabular summary of the co-authorship data obtained is provided in the Appendix.

Results

Co-authorship connections between the first A. M. Turing Award winner, Alan Perlis (1966), the most recent A. M. Turing Award winner, Leslie Lamport (2013), and 21 other Turing or von Neumann awardees are shown as a co-authorship subgraph in Fig. 1. Perlis' Turing Award honors his work in programming languages, one of the major subdisciplines within computer science. His direct co-authors John Backus (1977) and Peter Naur (2005) were also honored for work in programming languages. Programming-language researchers do not, however, form an exclusive clique; Backus' co-author John McCarthy (1971) began his career in cybernetics and was one of the founders of artificial intelligence (AI), another computer science subdiscipline. McCarthy's co-authors Marvin Minsky (1969) and Raj Reddy (1994) were also honored for work in AI; Reddy has also published in molecular biology (Ganapathiraju, Balakrishnan, Reddy and Klein-Seetharaman, 2008) is is therefore a cross-disciplinary broker. Fernando Corbato (1990), however, received his Turing Award for work in computer architectures, yet a third subdiscipline; Corbato also published in computational physics (e.g. Corbato and Switendick, 1963) and is therefore also a cross-disciplinary broker. Herbert Simon, a co-author of Minsky also honored for work in AI, is also well-known as a Nobel laureate in Economics (1978) and hence is also a cross-disciplinary broker. This mingling of subdisciplines continues throughout Fig. 1: Edward Feigenbaum (1994) and Allen Newell (1975) were honored for work in AI, Kenneth Iverson (1979) for work in programming languages and Frederick Brooks (1999) for work in computer architecture. Douglas Englebart (1997) was honored for work in user interfaces, including the invention of the “mouse” as a pointing device. Vinton Cerf (2004) and Robert Kahn (2004) were honored for their development of communication protocols for what would become the internet; research on networks and network security has since become a flourishing computer science subdiscipline. John von Neumann awardees Gordon Bell [1992], Frederick Brooks [1993], Carver Mead [1996], Butler Lampson [2001], Leslie Lamport [2008] and Edward McCluskey [2012] (award dates in brackets [] distinguish von Neumann Medal awardees) are architecture specialists. Ivan Sutherland (1988) is a graphics specialist, while Jim Gray (1998) is a database specialist.

Aside from Turing awardees Reddy, Simon and Corbato, Fig. 1 includes cross-disciplinary brokers to biology (Nobel laureates Joshua Lederberg and Francis Crick), medicine (Lederberg and physician-

6 http://dblp.uni-trier.de/db/; accessed Jan., 2015.

administrator Edward Shortliffe), psychology (cognitive psychologist David Rumelhart), neuroscience (neural modelers Terry Sejnowski and Christof Koch) and discrete mathematics (Andrew Odlyzko, Neil Sloane and Janusz Brzozowski). Odlyzko has an Erdős number of one, Brzozowski and Sloane have Erdős number two, Simon and Claude Shannon both have Erdős number three, while Crick and Lederberg have Erdős numbers four and five respectively;[7] hence the A. M. Turing and John von Neumann awardees shown here all have Erdős numbers less than or equal to six (see Appendix for a complete list) and hence distances from mathematics as a discipline of at most five.

The pattern of co-authorships among Turing and von Neumann awardees with different subdisciplinary specializations is continued in Fig. 2, which shows that Maurice Wilkes (1967), developer of the early EDSAC computer and hence an early pioneer of computer architecture, is a co-author of C. A. R. Hoare (1980), honored for his work in programming languages. Wilkes also published with John Lennard-Jones, a prominent physicist (Lennard-Jones, Wilkes and Bratt, 1939). Hoare's co-authors include programming-language specialists Niklaus Wirth (1984), Ole-Johan Dahl (2001) and Kristen Nygaard (2001). Edsger Dijkstra (1972), Robin Milner (1991), Amir Pnueli (1996), Michael Rabin (1976), Dana Scott (1976), Edmund Clarke (2007), Allen Emerson (2007), Joseph Sifakis (2007) and Barbara Liskov (2008) are also programming-language specialists, as is the most recent von Neumann awardee, James Gosling [2015]. Richard Karp (1985) is an algorithm specialist who has worked extensively in bioinformatics (e.g. Xing and Karp, 2001) and is a cross-disciplinary broker to biology; Cleve Moler [2014] is also an algorithm specialist. Karp's and Moler's Erdős numbers are two and Niklaus Wirth's is three; the largest Erdős number in Fig. 2 is Barbara Liskov's, eight.

Alan Perlis, Bulter Lampson and Leslie Lamport, who were widely separated in Fig. 1, are shown to be close in co-authorship space in Fig. 2; hence the co-authorship subgraph shown in Fig. 2 can be overlaid onto that shown in Fig. 1. Richard Karp, Michael Rabin and mathematician Noga Alon allow Fig. 2 to be overlaid in turn onto Fig. 3, which shows co-authorship connections to Donald Knuth (1974) and his collaborator Robert Floyd (1978), both honored for work in both algorithms and programming languages. Raj Reddy, Edward Feigenbaum and Jim Gray similarly allow Fig. 1 to be overlaid onto Fig. 3. It is likely that many other co-authorship paths exist between the scientists shown in these subgraphs; as the present searches were terminated when the closest other Turing or von Neumann awardee was identified, any such longer co-authorship paths were not examined.

Algorithm and formal language specialists John Hopcroft (1986) and J. D. Ullman, shown in Fig. 3, wrote the well-known textbook *Introduction to Automata Theory, Languages and Computation*; both received the John von Neumann Medal in 2010. Stephen Cook (1982), Robert Tarjan (1986), Juris Hartmanis (1993), Richard Stearns (1993), Manuel Blum (1995), Leslie Valiant (2010), Shafi Goldwasser (2012) and Silvio Micali (2012) are also algorithm specialists, as is Alfred Aho [2003]. John Hennessy and David Patterson, however, are architecture specialists, while Michael Stonebraker [2005] is a database specialist, Andrew C.-C. Yao (2000) is a cryptographer and Judea Pearl (2011) is an AI specialist. Network security experts Adi Shamir, Leonard Adleman and Ronald Rivest, Turing Award recipients for 2002, are overlaid onto the previous co-authorship subgraphs by the co-authorship connections shown in Fig. 4. No scientist in Figs. 3 or 4 is more than three steps from some cross-disciplinary broker, and hence from a co-authorship border of computer science.

As expected from the analysis of Newman (2001), many computer scientists have few co-authors.

7 http://www.oakland.edu/enp/erdpaths/, accessed Jan., 2015.

Surprisingly, A. M. Turing Award winners are near the co-authorship boundaries of computer science even when this is the case. Figure 5 shows co-authorship connections of Turing awardees Richard Hamming (1968) and Charles Bachman (1973). Hamming was a pioneer of digital encoding; he was also a physicist, and three of his few co-authors are physicists, including R. M. Bozorth (Bozorth and Hamming, 1953). Hamming's closest connection to other Turing awardees appears to be through physics to Claude Shannon (Fig. 1) and his collaborators. Charles Bachman developed some of the first database management systems; his closest connection to other Turing awardees appears to be through bioinformatics (S. Friend – R. W. Davis – D. Haussler – L. Valiant) to Leslie Valiant (2010).

Co-authorship connections of database management system developer Edgar Codd (1981), Kenneth Thompson (1983) and Dennis Ritchie (1983) are shown in Fig. 6. Codd is closer to biology than to the nearest other Turing awardee, Edward Feigenbaum. Thompson and Ritchie developed the UNIX operating system; Ritchie is only two steps from bioinformatics scientist Sorin Istrail, and can be linked to Fig. 1 through the path S. Istrail – G. G. Sutton – C. A. Fields – T. Eskridge – P. H. Hayes. Ritchie and Thompson receive Erdős numbers of six and seven, respectively, from G. G. Sutton's collaboration with E. S. Lander, who has an Erdős number of two. John Cocke (1987), the developer of reduced instruction set (RISC) architectures and Frances Allen (2006), honored for her work on optimizing programming-language compilers, are connected to neuroscience via Geoff Hinton, and hence to Fig. 1, in Fig. 7. Numerical analyst William Kahan (1989) is closer to both physics and mathematics, via cross-disciplinary broker Hans Weinberger, than to Allen, the closest other Turing awardee. Weinberger is a co-author of George Pólya, who has Erdős number two; hence Kahan's Erdős number is at most four and Allen's and Cocke's are at most seven and eight respectively.

Figure 8 shows that this close proximity to cross-disciplinary brokers also characterizes personal-computer pioneers Alan Kay (2003) and Charles Thacker (2009). Kay's closest connection to other awardees appears to be through AI researcher J. A. Feldman to D. H. Ballard (Fig. 1); Thacker links to Figs. 1 and 2 through Butler Lampson and to Fig. 3, via programming language specialist Susan Graham [09] to J. D. Ullman. Computer graphics and animation developer Edwin Catmull [2006] is linked to Fig. 1 through Allen Newell, as shown in Fig. 9.

Discussion

The results shown in Figs. 1 – 9 can be summarized as follows: A. M. Turing Award and John von Neumann Medal winners from 1966 to 2015 are separated from some other Turing or von Neumann awardee by at most 1.4 co-authorship steps on average, and are separated by at most 1.6 co-authorship steps, again on average, from some cross-disciplinary broker and hence from some Klavans and Boyack (2009) consensus discipline other than computer science. If the average of 9.7 co-authorship steps between computer scientists from 1995 to 1999 (Newman, 2001) is at all representative of this larger period, Turing and von Neumann awardees are far closer, on average, to the boundaries of computer science than computer scientists are, on average, to each other. A recent study of co-authorship patterns of late-career computer scientists (Cabanac, Hubert and Milard, 2015), while not directly comparable to that of Newman (2001), suggests that while the average number of co-authors per paper in computer science has not changed significantly, the average number of co-authors per (late-career) author has perhaps increased, from 3.6 co-authors on average for all authors in Newman (2001) to a median of 20 co-authors per late-career author in Cabanac, Hubert and Milard (2015). The number of papers per author in this latter study, however, has an imposed lower cut-off of 15, a factor of 6x the average of 2.5 papers per author reported by Newman (2001); it is difficult, therefore, to estimate the potential impact of this apparently larger number of co-authors per author on either the average distance between authors of computer science papers or the diameter of the computer-science co-authorship graph. Even if the average distance between computer science authors reported by Newman (2001) were cut in half, however, it would still be over twice as large as the average distance found here between A. M. Turing Award or John von Neumann Medal winners and at least one other discipline.

While computer science comprises a number of subdisciplines, the Turing and von Neumann awardees do not form exclusive subdisciplinary cliques. Artificial intelligence researcher John McCarthy, for example, is a co-author of programming-language researcher John Backus and computer architecture researcher Fernando Corbato (Fig. 1); similarly, algorithms researcher Richard Karp is a co-author of programming-language researcher Michael Rabin (Fig. 2) and artificial intelligence researcher Judea Pearl (Fig. 3). This absence of subdisciplinary cliques effectively masks the differences in subdisciplinary distributions of the Turing and von Neumann awards. Alan Turing is widely regarded as the principal founder of AI; he also laid much of the groundwork for formal language semantics and hence for the development of programming languages. Seven of the 61 A. M. Turing Award winners (11.5%) are AI researchers; 18/61 (29.5%) are programming language specialists. John von Neumann is best known for the von Neumann architecture employed in most current computers. Ten of the 27 John von Neumann Medal winners (37.0%) are architecture specialists; none are AI researchers. Despite these differences, neither Turing nor von Neumann awardees form cliques among themselves. Hence while computer science subdisciplines have remained reasonably well-defined over several decades (Chakraborty, Sikdar, Ganguly and Mukherjee, 2014), their most prominent representatives appear to collaborate across subdisciplinary boundaries quite frequently. The research areas honored by Turing or von Neumann awards do not, moreover, appear to form significant clusters in time, nor do the subdisciplines honored evidently track the dominant computer science subdisciplines as revealed by time-dependent citation analysis (cf. Chakraborty, Sikdar, Ganguly and Mukherjee, 2014, Fig. 7).

While most Turing or von Neumann awardees (58/74 or 78%) are direct co-authors of at least one other awardee, some are sufficiently distant, at least along the paths identified here, to connect to other awardees only through co-authors in some another discipline. Seven Turing or von Neumann awardees are identified as cross-disciplinary brokers: Richard Hamming, Fernando Corbato and Jim Gray to physics, Herbert Simon to economics, Richard Karp and Raj Reddy to biology and Cleve Moler to mathematics. If A. M. Turing and John von Neumann awardees form the "center" of computer science as defined by recognized scientific accomplishment, then this "center" is not bounded exclusively by computer scientists.

During the first decade of A. M. Turing Awards, 1966 – 1975, the 11 awardees were on average 1.4 co-authorship steps from some other discipline; five were closest to physics, or as close to physics as to any other discipline, while three were closest to economics, or as close to economics as to any other discipline. During the last decade investigated for the Turing award, 2004 – 2013, the 14 awardees were on average 2.0 co-authorship steps from some other discipline; 11 of the 14 (78%) were closest to the biomedical sciences, including neuroscience, or as close to the biomedical sciences as to any other discipline. This 0.6 step (43%) increase in co-authorship distance may reflect the maturation of computer science as a discipline. In the 1960's and early 1970's, most practicing computer scientists had been trained in some other discipline. Of the 11 winners of the A. M. Turing award between 1966 and 1975, only Edsger Dijkstra had a PhD in Computer Science; Perlis, Hamming, Minsky, McCarthy and Knuth all had PhDs in Mathematics, Wilkes', Simon's and Newell's were in Physics, Political Science and Industrial Administration (under Simon) respectively, while Wilkinson and Bachman bypassed PhDs altogether. In contrast, eight of the 14 A. M. Turing awardees between 2004 and 2013, Kahn, Cerf, Sifakis, Clarke, Liskov, Valiant, Pearl and Goldwasser, have PhDs in either Computer Science or Electrical Engineering, which is considered to be a subdiscipline of computer science by Klavans and Boyack (2009) and is often combined with computer science into a single academic department. Emerson, Micali and Lamport have PhDs in Mathematics, Naur's is in Astronomy, and neither Allen nor Thacker have PhDs.

Over the entire period investigated, 42 A. M. Turing or John von Neumann awardees (57%) were closest to the biomedical sciences, including neuroscience, or as close to the biomedical sciences as to any other discipline. Based on a century (1910 – 2010) of cross-disciplinary citation data, Chen, Arsenault, Gingras and Larivière (2014) estimate that engineering and technology disciplines, specifically computer science, began to influence biochemistry and molecular biology, now the core disciplines of biomedical science, in 1990 (see their Fig. 8). An examination of specific research areas, however, allows this date to be pushed back considerably. Alan Turing himself developed algorithmic models of biological pattern formation (Turing, 1952) that are still used to study morphogenesis today (e.g. Meinhardt, 2009). The “perceptron” algorithm introduced by Rosenblatt (1958) is a direct forerunner of current neural modeling programs as well as providing the basis for molecular sequence analysis tools (e.g. Stormo, Schneider, Gold and Ehrenfeucht, 1982). The DENDRAL project (Lederberg *et al.*, 1969) was an early collaboration between a Nobel laureate in Physiology or Medicine (J. Lederberg, 1958) and an A. M. Turing awardee (E. A. Feigenbaum, 1994) and was a forerunner of current molecular spectrometry software. Medical diagnosis was one of the first application areas for expert systems technology, an early product of AI research (e.g. Shortliffe, Axline, Buchanan, Merigan and Cohen, 1973). The GenBank (US) and EMBL (Europe) DNA sequence databases were established in 1982 (Kanehisa, Fickett and Goad, 1984), well before internet (then ARPANET) links were widely available in universities. By the mid-1990s, the critical role of integrated bioinformatics systems, and hence of ideas and methods from computer science, in molecular biology and genomics was almost universally acknowledged (e.g. Fields, 1996). Any discussion of formal measures of the intellectual impact or significance of specific collaborations has been avoided in the present analysis in order to focus on co-authorship; it is clear, however, that at least in the case of bioinformatics, the cross-disciplinary excursions of computer scientists (as well as mathematicians and physicists) have been extraordinarily productive. Given this historical context, it is not surprising that A. M. Turing and John von Neumann awardees are often close to biomedicine, or that their proximity to biomedicine has increased with time.

Conclusion

What counts as a “scientific discipline” remains a matter of discussion (e.g. Jacobs and Frickel, 2009; Sugimoto and Weingart, 2015) and the number of intellectual activities considered to be disciplines has increased dramatically over the past few decades. Nominally discipline-specific, achievement-based awards made to prominent individuals, such as Nobel Prizes or the A. M. Turing Award and John von Neumann Medal, provide one way of informally identifying the intellectual “centers” of disciplines amidst this flux. It has been shown here that computer science, still a small science discipline, shares a significant characteristic with biomedicine, now a big science discipline: in both, many of the most prominent “central” researchers are close, in terms of co-authorship, to other disciplines. A. M. Turing

Award or John von Neumann Medal winners from 1966 to 2015 are, in fact, even closer to other disciplines than are Nobel laureates in Physiology of Medicine from 1991 to 2010 (Fields, in press). Like Nobel laureates in Physiology of Medicine, A. M. Turing Award and John von Neumann Medal winners are closer, on average, to the boundaries of other disciplines than the members of their own discipline are, on average, to each other. If this curious situation is not due to the vast collaborations and liberal co-authorship policies typical of big science, to what is it due?

One possible answer, of course, is that computer science is still a young science; there is considerable field mobility both into and out of computer science, so co-authors who either have been or will at some future time be associated with other disciplines are readily available. Such co-authors may be attracted to A. M. Turing or John von Neumann awardees, or to prominent individuals who later become A. M. Turing or John von Neumann awardees, by well-understood preferential attachment mechanisms (e. g. Barabási *et al*., 2002). Another possibility is that the more prominent researchers in any discipline, computer science included, may have more freedom to explore interdisciplinary topics and develop interdisciplinary co-authorship connections than do less prominent researchers, or may take advantage of what freedom they do have more frequently. The proximity of A. M. Turing and John von Neumann awardees to the biomedical sciences during a period of rapid technological progress and conceptual development suggests a third possibility: that inter- or cross-disciplinary research is intellectually exciting and rewarding. As in the cases of bioinformatics in the 1990s or even, a few decades earlier, of computer science itself, such cross-disciplinary work sometimes leads to the development of entirely new areas of research, of which the most prominent early pioneers become the leaders. The present findings are consistent with any or all of these mechanisms, and indeed suggest that they may work in combination. What the present findings challenge is the still-common idea that inter- or cross-disciplinary research is intellectually marginal or peripheral and has relatively little academic value. Were this the case, one would not expect any discipline's most prominent representatives to so frequently engage in it.

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Figure Captions

Fig. 1: Co-authorship connections of the first A. M. Turing awardee, Alan Perlis (1966) and several of his colleagues, showing cross-disciplinary connections to mathematics, physics, biology, psychology, medicine and neuroscience. A. M. Turing Award dates are shown in parentheses (); John von Neumann Medal dates are shown in brackets [].

Fig. 2: Co-authorship connections of the second A. M. Turing awardee, Maurice Wilkes (1967) and colleagues, showing cross-disciplinary connections to mathematics, physics, chemistry, biology and neuroscience. This subgraph joins to that shown in Fig. 1 through both Alan Perlis, Bulter Lampson and Leslie Lamport.

Fig. 3: Co-authorship connections of A. M. Turing awardee Donald Knuth (1974) and colleagues, showing cross-disciplinary connections to mathematics, physics, chemistry and biology.

Fig. 4: Co-authorship connections of A. M. Turing awardees Leonard Adleman (2002), Ronald Rivest (2002) and Adi Shamir (2002) to other A. M. Turing awardees and to both mathematics and biology.

Fig. 5: Co-authorship connections of A. M. Turing awardees a) Richard Hamming (1968) and b) Charles Bachman (1973). In each case, the shortest identified co-authorship path to other A. M. Turing or John von Neumann awardees traverses some other discipline.

Fig. 6: Co-authorship connections of A. M. Turing awardees a) Edgar Codd (1981) and b) Kenneth Thompson (1983) and Dennis Ritchie (1983), showing the shortest paths found to cross-disciplinary brokers or (for E. Codd) other A. M. Turing awardees.

Fig. 7: Co-authorship connections of A. M. Turing awardees John Cocke (1987), William Kahan (1989) and Frances Allen (2006). The shortest identified co-authorship paths to other A. M. Turing or John von Neumann awardees traverse neuroscience to Fig. 1.

Fig. 8: Co-authorship connections of A. M. Turing awardees a) Alan Kay (2003) and b) Charles Thacker (2009). Kay's shortest identified co-authorship paths to other A. M. Turing awardees is through D. H. Ballard to Fig. 1.

Fig. 9: Co-authorship connections of John von Neumann Medal winner Edwin Catmull [2006], showing connections to Turing awardee Allen Newell (1975) and to psychology.

Appendix

Table 1: Summary of the co-authorship results for A. M. Turing Award winners shown as subgraphs in Figs. 1 – 9. A two-digit date in brackets [] indicates an individual who is also a John von Neumann Medal recipient. Symbols are d_r = co-authorship distance to nearest A. M. Turing Award or John von Neumann Medal recipient, n_r = number of A. M. Turing Award or John von Neumann Medal recipients at distance d_r, d_b = co-authorship distance to nearest cross-disciplinary broker, n_b = number of brokers at distance d_b, n_E = Erdős number. Routes to Erdős are given by * = http://www.oakland.edu/enp/thedata/; ** = http://www.oakland.edu/enp/erdpaths/. Note that some Turing Award and von Neumann medal recipients appear in multiple subgraphs.

Year	Recipient	Specialty	d_r	n_r	d_b	n_b	Discipline(s)	n_E	via
1966	Alan Perlis	Prog. Lang.	1	4	2	2	Phys, Biol	5	C. Shannon**
1967	M. V. Wilkes [97]	Architecture	1	1	1	1	Phys	5	G. E. Forsythe*
1968	R. W. Hamming	Architecture	5	2	0	1	Phys	7	C. E. Shannon**
1969	Marvin Minsky	Artif. Intell.	1	2	1	1	Econ	4	C. E. Shannon**
1970	J. H. Wilkinson	Algorithms	3	1	1	1	Math	3	G. H. Golub*

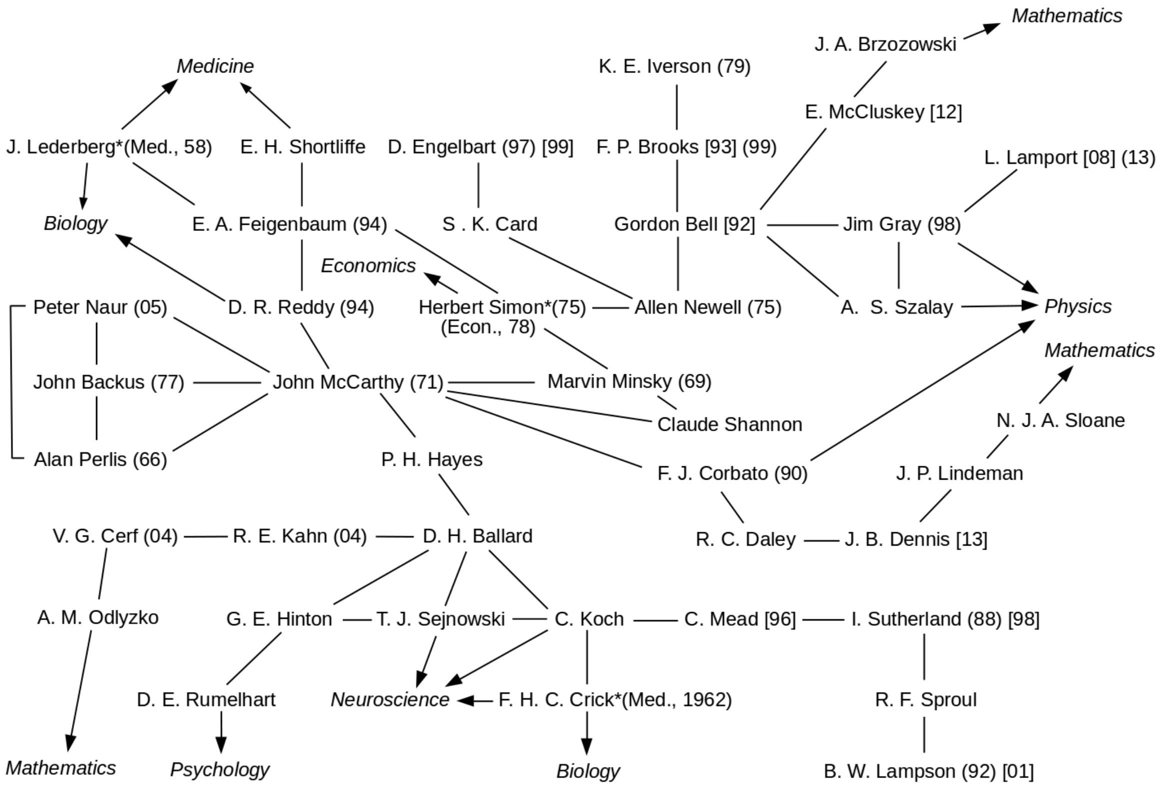
1971	John McCarthy	Artif. Intell.	1	5	1	1	Phys	4	C. Shannon**
1972	E. W. Dijkstra	Prog. Lang.	1	2	3	1	Phys	6	C. Shannon*
1973	C. W. Bachman	Databases	1	4	4	2	Biol	8	D. Haussler*
1974	D. E. Knuth [95]	Algorithms	1	1	1	1	Math	2	**
1975	Herbert Simon	Artif. Intell.	1	3	0	1	Econ	3	**
"	Allen Newell	Artif. Intell.	1	2	1	1	Econ	4	H. Simon**
1976	Dana S. Scott	Prog. Lang.	1	1	2	2	Math, Biol	3	N. Alon*
"	M. O. Rabin	Prog. Lang.	1	3	1	2	Math, Biol	2	N. Alon*
1977	John Backus	Prog. Lang.	1	3	2	2	Phys, Biol	5	C. Shannon**
1978	R. W. Floyd	Algorithms	1	4	2	3	Math, Biol	3	D. E. Knuth*
1979	K. E. Iverson	Prog. Lang.	1	1	3	2	Phys	6	J. Brzozowski**
1980	C. A. R. Hoare [11]	Prog. Lang.	1	5	2	2	Math, Phys	4	G. E. Forsythe*
1981	Edgar F. Codd	Databases	3	1	2	1	Biol	7	D. Haussler**
1982	S. A. Cook	Algorithms	4	2	2	1	Biol	7	D. E. Knuth*
1983	Dennis Ritchie	Operating Syst.	1	1	2	1	Biol	6	E. S. Lander*
"	K. L. Thompson	Operating Syst.	1	1	3	1	Biol	7	E. S. Lander*
1984	N. E. Wirth	Prog. Lang.	1	1	1	1	Math	3	G. E. Forsythe*
1985	R. M. Karp	Algorithms	1	7	0	1	Biol	2	*
1986	J. E. Hopcroft [10]	Algorithms	1	6	1	1	Biol	3	R. M. Karp*
"	R. E. Tarjan	Algorithms	1	3	1	2	Biol	3	E. L. Lawler*
1987	John Cocke [94]	Architecture	1	1	3	1	Neuro	8	G. Pólya*
1988	I. Sutherland [98]	Graphics	1	1	2	1	Neuro	6	P. Baldi*
1989	W. M. Kahan	Algorithms	3	1	1	1	Phys, Math	4	G. Pólya *
1990	F. J. Corbato	Architecture	1	1	0	1	Phys	5	C. Shannon**
1991	A. J. R. G. Milner	Prog. Lang.	1	1	3	1	Phys	5	G. E. Forsythe*
1992	B. W. Lampson [01]	Architecture	1	1	3	2	Neuro	6	R. M. Karp*
1993	J. Hartmanis	Algorithms	1	5	1	1	Biol	4	R. M. Karp*
"	R. E. Stearns	Algorithms	1	1	2	1	Biol	5	R. M. Karp*
1994	E. A. Feigenbaum	Artif. Intell.	1	3	1	4	Biol, Med, Econ	4	H. Simon**
"	D. R. Reddy	Artif. Intell.	1	3	0	1	Biol	5	H. Simon**
1995	Manuel Blum	Algorithms	1	6	1	1	Math	2	N. Alon*

1996	Amir Pnueli	Prog. Lang.	1	1	2	1	Biol	5	R. M. Karp*
1997	D. Engelbart [99]	User Interface	2	1	3	1	Econ	6	H. Simon**
1998	J. N. Gray	Databases	1	3	0	1	Phys	5	R. M. Karp*
1999	Frederick Brooks [93]	Architecture	1	2	2	2	Phys	5	J. Brzozowski*
2000	A. C.-C. Yao	Security	2	1	2	1	Biol	4	R. M. Karp*
2001	O.-J. Dahl [02]	Prog. Lang.	1	2	3	2	Math, Phys	5	G. E. Forsythe*
“	K. Nygaard [02]	Prog. Lang.	1	2	3	2	Math, Phys	5	G. E. Forsythe*
2002	A. Shamir	Security	1	2	2	3	Math, Biol	3	A. M. Odlyzko*
“	R. L. Rivest	Security	1	8	1	1	Biol	3	A. M. Odlyzko*
“	L. M. Adleman	Security	1	2	1	2	Math, Biol	2	A. M. Odlyzko*
2003	Alan Kay	Personal Comp.	3	1	1	1	Psych	8	F. H. C. Crick**
2004	R. E. Kahn	Internet	3	2	2	3	Math, Neuro	3	A. M. Odlyzko*
“	V. G. Cerf	Internet	4	2	1	1	Math	2	A. M. Odlyzko*
2005	Peter Naur	Prog. Lang.	1	3	2	2	Phys, Biol	5	C. Shannon**
2006	F. E. Allen	Prog. Lang.	1	1	3	1	Neuro	7	G. Pólya*
2007	J. Sifakis	Prog. Lang.	1	3	3	2	Biol, Neuro	6	R. M. Karp*
“	E. A. Emerson	Prog. Lang.	1	2	1	2	Neuro	5	R. M. Karp*
“	E. M. Clarke	Prog. Lang.	1	2	3	1	Neuro	6	R. M. Karp*
2008	Barbara Liskov [04]	Prog. Lang.	2	1	5	1	Neuro	8	R. M. Karp*
2009	C. P. Thacker [07]	Personal Comp.	1	1	2	1	Neuro	7	R. M. Karp*
2010	Leslie G. Valiant	Algorithms	1	1	1	2	Chem, Biol	3	D. Haussler*
2011	Judea Pearl	Artif. Intell.	1	2	1	1	Biol	3	R. M. Karp*
2012	Silvio Micali	Algorithms	1	3	2	3	Math, Biol	3	N. Alon*
“	S. Goldwasser	Algorithms	1	2	1	1	Math	2	L. Lovász*
2013	Leslie Lamport [08]	Architecture	1	2	1	1	Phys	6	R. M. Karp*

Table 2: Summary of the co-authorship results for John von Neumann Medal recipients who are not also A. M. Turing Award winners. Symbols are as in Table 1, except dates refer to John von Neumann Medal award dates.

Year	Recipient	Specialty	d_r	n_r	d_b	n_b	Discipline(s)	n_E	via
1992	Gordon Bell	Architecture	1	4	1	2	Phys	5	H. Simon**
1996	Carver Mead	Architecture	1	1	1	1	Neuro	5	P. Baldi*
2000	D. A. Patterson	Architecture	1	2	1	1	Biol	3	R. M. Karp*
“	J. L. Hennessy	Architecture	1	1	2	1	Biol	4	R. M. Karp*
2003	Alfred Aho	Algorithms	1	2	1	1	Phys	4	R. M. Karp*
2005	M. Stonebraker	Databases	1	3	1	1	Phys	4	R. M. Karp*
2006	Edwin Catmull	Graphics	4	1	4	1	Psych	8	H. Simon**
2009	Susan Graham	Prog. Lang.	2	2	1	3	Biol	6	R. M. Karp*
2010	Jeffery Ullman	Algorithms	1	4	1	1	Biol	4	D. E. Knuth*
2012	E. McCluskey	Architecture	1	1	1	1	Math	3	J. Brzozowski*
2013	Jack Dennis	Operating Syst.	2	1	2	2	Math, Phys	4	N. J. A. Sloane*
2014	Cleve Moler	Algorithms	2	1	0	1	Math	3	G. E. Forsythe*
2015	J. A. Gosling	Prog. Lang.	2	1	2	1	Psych	7	G. E. Forsythe*

Fig. 1


Mathematics
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Medicine
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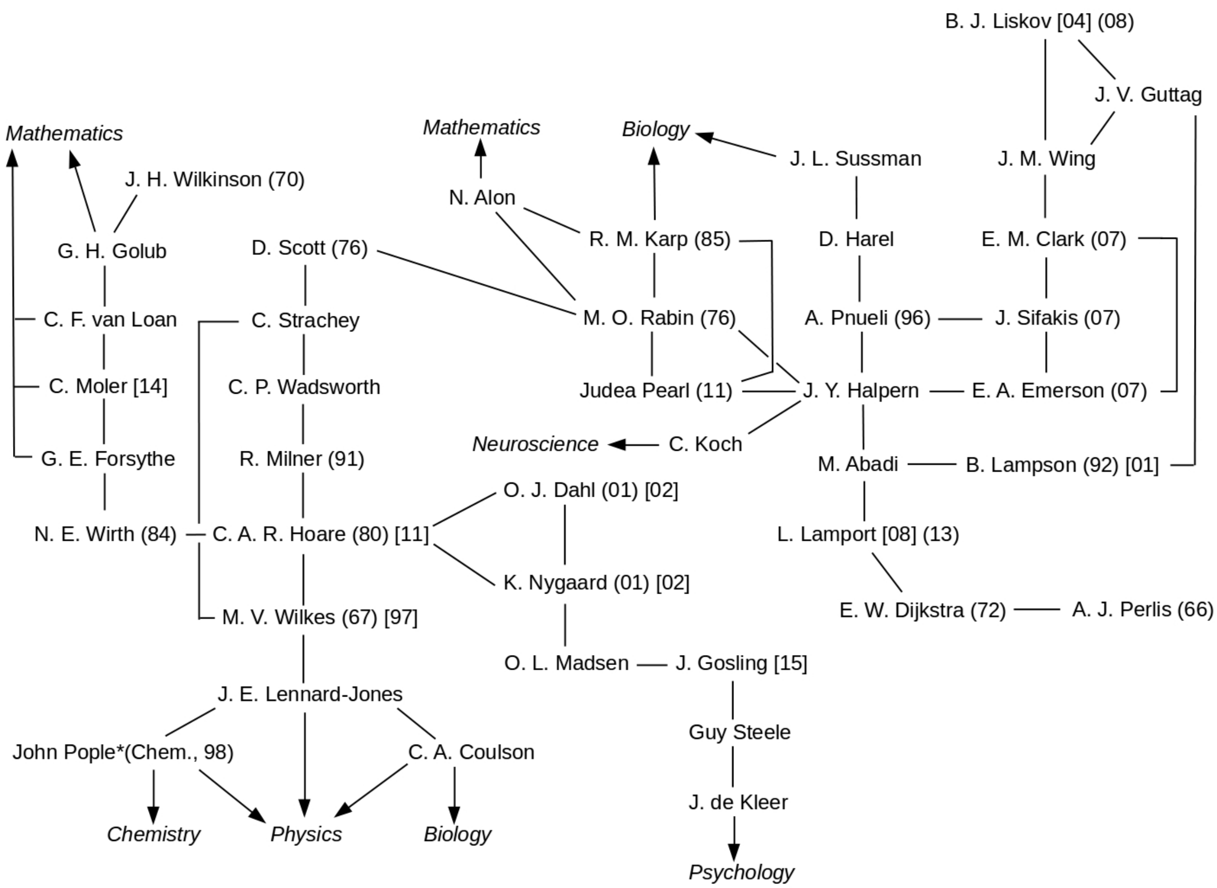
E. McCluskey [12]
J. Lederberg*(Med., 58)
E. H. Shortliffe
D. Engelbart (97) [99]
F. P. Brooks [93] (99)
L. Lamport [08] (13)
Biology
E. A. Feigenbaum (94)
S . K. Card
Gordon Bell [92]
Jim Gray (98)
Economics
Peter Naur (05)
D. R. Reddy (94)
Herbert Simon*(75)
(Econ., 78)
Allen Newell (75)
A. S. Szalay
Physics
Mathematics
John Backus (77)
John McCarthy (71)
Marvin Minsky (69)
Claude Shannon
N. J. A. Sloane
Alan Perlis (66)
P. H. Hayes
F. J. Corbato (90)
J. P. Lindeman
V. G. Cerf (04)
R. E. Kahn (04)
D. H. Ballard
R. C. Daley
J. B. Dennis [13]
A. M. Odlyzko
G. E. Hinton
T. J. Sejnowski
C. Koch
C. Mead [96]
I. Sutherland (88) [98]
D. E. Rumelhart
Neuroscience
F. H. C. Crick*(Med., 1962)
R. F. Sproul
Mathematics
Psychology
Biology
B. W. Lampson (92) [01]

Fig. 2



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Mathematics
Biology
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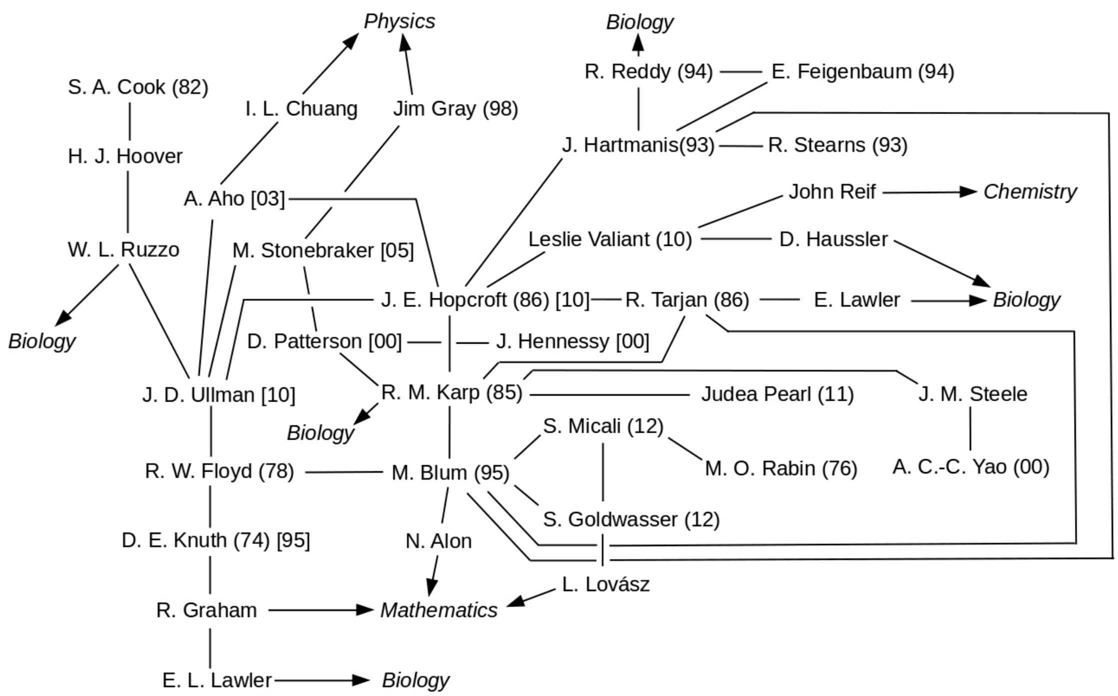
J. M. Wing
J. H. Wilkinson (70)
N. Alon
G. H. Golub
D. Scott (76)
R. M. Karp (85)
D. Harel
E. M. Clark (07)
C. F. van Loan
C. Strachey
M. O. Rabin (76)
A. Pnueli (96)
J. Sifakis (07)
C. Moler [14]
C. P. Wadsworth
Judea Pearl (11)
J. Y. Halpern
E. A. Emerson (07)
Neuroscience
C. Koch
G. E. Forsythe
R. Milner (91)
M. Abadi
B. Lampson (92) [01]
O. J. Dahl (01) [02]
N. E. Wirth (84)
C. A. R. Hoare (80) [11]
L. Lamport [08] (13)
K. Nygaard (01) [02]
M. V. Wilkes (67) [97]
E. W. Dijkstra (72)
A. J. Perlis (66)
O. L. Madsen
J. Gosling [15]
J. E. Lennard-Jones
Guy Steele
John Pople*(Chem., 98)
C. A. Coulson
J. de Kleer
Chemistry
Physics
Biology
Psychology

Fig. 3



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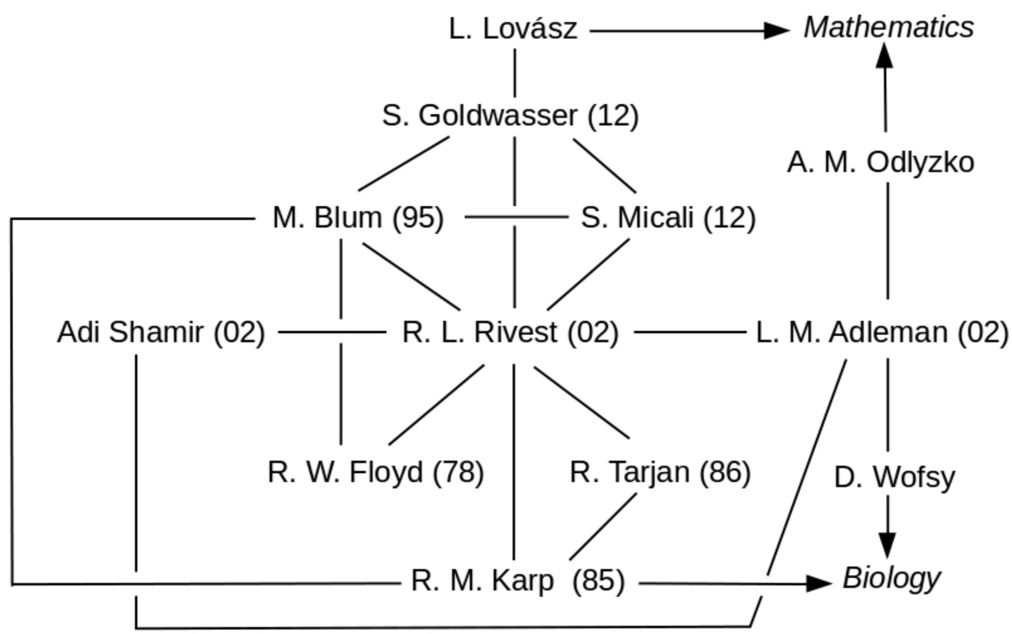
R. Reddy (94)
E. Feigenbaum (94)
S. A. Cook (82)
I. L. Chuang
Jim Gray (98)
H. J. Hoover
J. Hartmanis(93)
R. Stearns (93)
A. Aho [03]
John Reif
Chemistry
W. L. Ruzzo
M. Stonebraker [05]
Leslie Valiant (10)
D. Haussler
J. E. Hopcroft (86) [10]
R. Tarjan (86)
E. Lawler
Biology
Biology
D. Patterson [00]
J. Hennessy [00]
J. D. Ullman [10]
R. M. Karp (85)
Judea Pearl (11)
J. M. Steele
Biology
S. Micali (12)
R. W. Floyd (78)
M. Blum (95)
M. O. Rabin (76)
A. C.-C. Yao (00)
S. Goldwasser (12)
D. E. Knuth (74) [95]
N. Alon
L. Lovász
R. Graham
Mathematics
E. L. Lawler
Biology

Fig. 4



L. Lovász
Mathematics
S. Goldwasser (12)
A. M. Odlyzko
M. Blum (95)
S. Micali (12)
Adi Shamir (02)
R. L. Rivest (02)
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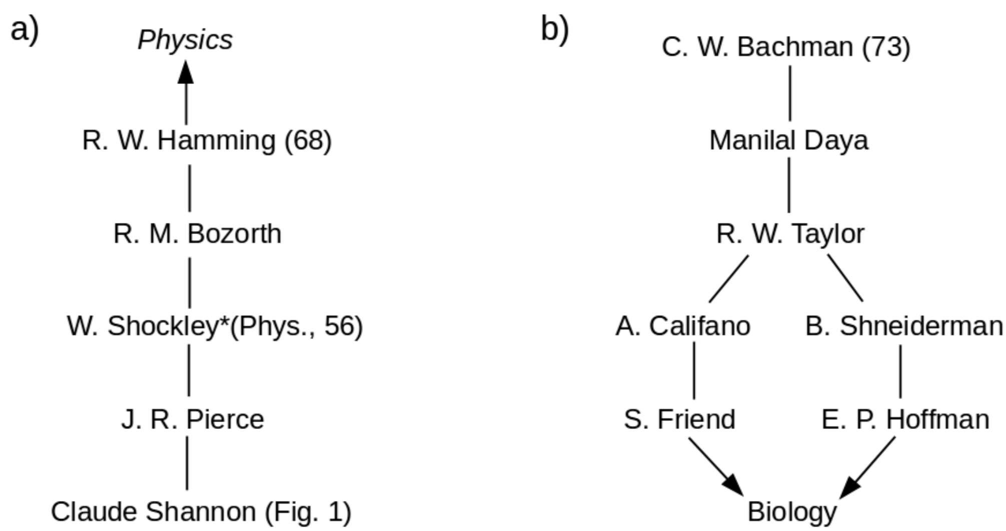
R. W. Floyd (78)
R. Tarjan (86)
D. Wofsy
R. M. Karp (85)
Biology

Fig. 5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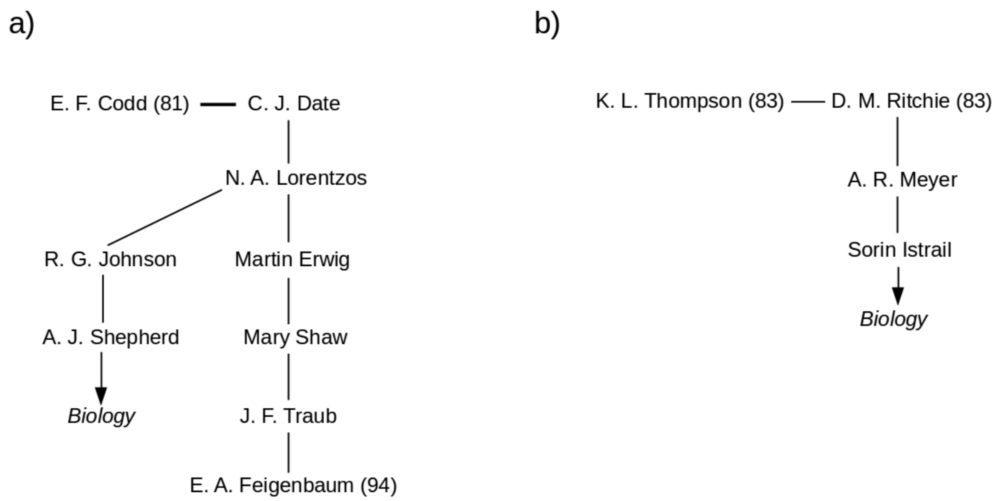
R. M. Bozorth
W. Shockley*(Phys., 56)
J. R. Pierce
Claude Shannon (Fig. 1)
b)
C. W. Bachman (73)
Manilal Daya
R. W. Taylor
A. Califano
B. Shneiderman
S. Friend
E. P. Hoffman
Biology

Fig. 6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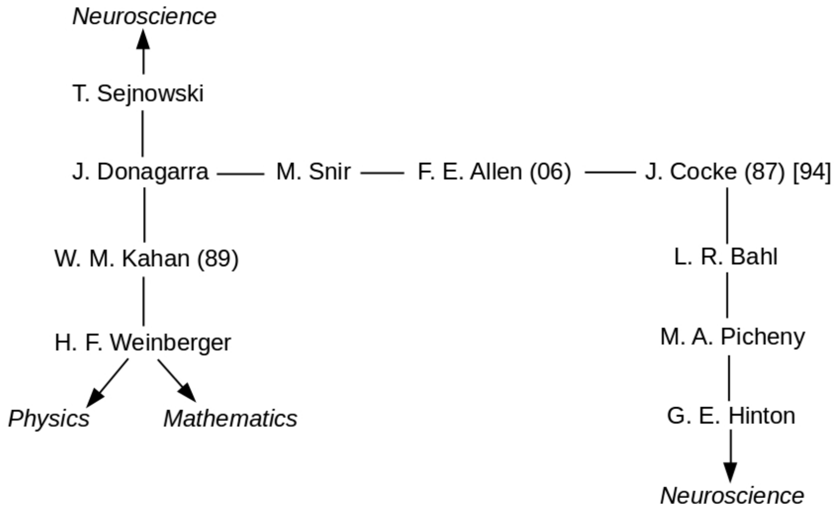
R. G. Johnson
Martin Erwig
A. J. Shepherd
Mary Shaw
Biology
J. F. Traub
E. A. Feigenbaum (94)
b)
K. L. Thompson (83)
D. M. Ritchie (83)
A. R. Meyer
Sorin Istrail
Biology

Fig. 7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M. Snir
F. E. Allen (06)
J. Cocke (87) [94]
W. M. Kahan (89)
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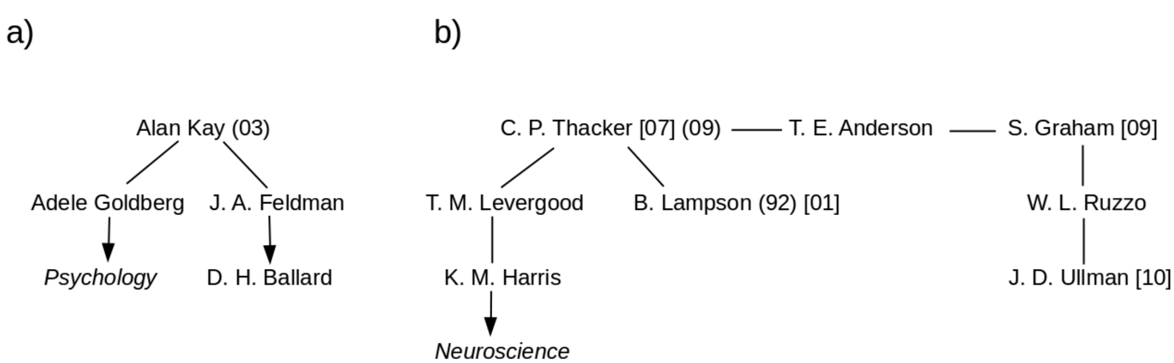
H. F. Weinberger
M. A. Picheny
Physics
Mathematics
G. E. Hinton
Neuroscience

Fig. 8


a)
b)
Alan Kay (03)
Adele Goldberg
J. A. Feldman
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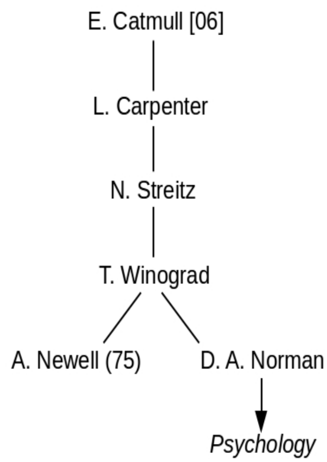
D. H. Ballard
C. P. Thacker [07] (09)
T. E. Anderson
S. Graham [09]
T. M. Levergood
B. Lampson (92) [01]
W. L. Ruzzo
K. M. Harris
J. D. Ullman [10]
Neuroscience

Fig. 9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L. Carpenter
N. Streitz
T. Winograd
A. Newell (75)
D. A. Norman
Psychology